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(NASA-TM-78877) CYCLIC OXIDATION OF COATED
OXIDE DISPERSION STRENGTHENED (ODS) ALLOYS
IN HIGH VELOCITY GAS STREAMS AT 1100 DEG C
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CYCLIC OXIDATION OF COATED OXIDE DISPERSION STRENGTHENED (ODS)
ALLOYS IN HIGH VELOCITY GAS STREAMS AT 1100° C

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May, 1978



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16. Abstract Several overlay coatings on ODS NiCrAl's were tested in Mach 1 and Mach 0.3 burner rigs to examine oxidation and thermal fatigue performance. The coatings were applied by various methods. Based on weight change, macroscopic, and metallographic observations in Mach 1 tests Nascoat 70 on TD-NiCrAl exhibited the best oxidation resistance. In Mach 0.3 tests PWA 267 and ATD-1, about equally, were the best coatings on YD-NiCrAl (Nascoat 70 was not tested in Mach 0.3 rigs).					
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SUMMARY

An exploratory study was conducted to examine the cyclic oxidation performance of several overlay coatings on ODS NiCrAl vane alloys at 1100⁰ C in Mach 1 and Mach 0.3 burner rigs. The coatings were applied by various methods. Coatings designated PWA 267 and ATD-1 were applied by physical vapor deposition; Nascoat 70 was sputter deposited (a lower Al content NiCrAl) followed by pack aluminizing. A PWA 267 + Pt coating was applied by physical vapor deposition and subsequently platinized by sputtering. Evaluations were based on weight change, macroscopic, and metallographic observations.

In general, Nascoat 70 on TD-NiCrAl exhibited the best Mach 1 oxidation resistance followed closely by PWA 267. The thermal fatigue resistance of TD-NiCrAl, however, was the same with either coating. The PWA 267 + Pt coating on TD-NiCrAl was the least protective, offering protection for less than 600 hours.

PWA 267 and ATD-1 coatings offered about equal protection to YD-NiCrAl in Mach 0.3 tests.

After tests, all coated specimens showed porosity in the ODS alloy substrates.

INTRODUCTION

Oxide dispersion strengthened (ODS) nickel-base alloys appear to have potential applications in hot section components of advanced civilian and military gas turbine engines. They possess the attractive characteristics of high temperature stress-rupture properties, high melting points, good thermal stability and fatigue resistance. Initially, they have been considered for use at 1100⁰ C for times up to at least 3000 hours as turbine guide vanes (refs. 1 and 2). One major class of ODS alloys that are of special interest, the thoria or yttria oxide dispersion strengthened (ODS) NiCrAl alloys (TD-NiCrAl or YD-NiCrAl) would also be expected to have some inherent oxidation resistance by forming a dense, adherent, nonvolatile Al₂O₃ scale. The work of Deadmore, et al. (ref. 2), showed that the better ODS NiCrAl alloys indeed had good cyclic oxidation resistance in high velocity (Mach 0.3 and/or Mach 1)

burner rig tests at 1100°C for times up to about 400 hours. This preliminary work, however, suggested that additional protection might be necessary for life-times in excess of 500 hours at 1100°C .

Previous experiences with turbine alloys at NASA's Lewis Research Center and other laboratories have shown that overlay coatings offer considerable promise for extending the time and/or temperature usefulness of the alloys. The best coatings for improved oxidation resistance are those that form aluminum-rich scales, primarily Al_2O_3 (refs. 3 through 11). These coatings on ODS NiCrAl alloys would offer initial protection until they are degraded by depletion of aluminum within the coatings and/or by erosion damage. Thereafter, the ODS NiCrAl alloys would be protected by their own inherent oxidation resistance.

Thus, the work reported here was to examine the cyclic oxidation performance of several commercial and experimental coatings on ODS NiCrAl alloys at 1100°C in high velocity gas streams which simulate those conditions encountered in advanced gas turbines. These performance data may be of use as baseline data for future coating studies. Initially, the cyclic oxidation tests were conducted on a candidate TD-NiCrAl alloy with three overlay coatings in a Mach 1 burner rig. Subsequent tests were conducted on a new, higher strength YD-NiCrAl alloy coated with two overlay coatings in a lower velocity Mach 0.3 burner rig. The work of reference 2 indicated that the Mach 0.3 tests were only slightly less severe than the Mach 1 tests. The performance of the coated ODS alloys was examined on the basis of specific weight change, visual examination, and cross-sectional metallographic analysis. These were supplemented with limited X-ray diffraction and microprobe analyses.

MATERIAL, APPARATUS, AND PROCEDURES

The compositions of the ODS NiCrAl alloys coated and tested are listed in table I. The TD-NiCrAl alloy (3933) was obtained under contract NAS3-13490 from Fansteel, Inc. (ref. 12). The YD-NiCrAl alloy (AT-264), a higher aluminum modification of HA-8077 alloy, was produced by Cabot Corp. under contract NAS3-17806 (ref. 1). These alloys were received in the extruded and heat-treated condition. For coating and testing, the alloys were machined into specimens of the geometries and dimensions shown in figure 1. In the Mach 1 tests, very high thermal stresses are generated at the small radiused, leading edges of the specimens. Usually this test configuration leads to early thermal fatigue cracking and high weight losses. The shape of the Mach 0.3 test specimens, however, generally does not allow generation of sufficiently high thermal stresses to cause early cracking at the leading edges because of the large radius.

The machined test specimens were coated with the overlay coatings listed in table II. The coatings were applied by either physical vapor deposition (PVD), sputter deposition (SD), pack cementation (PC), or a combination of these methods. The Pratt & Whitney PWA 267 + Pt coating was applied by PVD of a high aluminum containing NiCrAlY alloy followed by SD of a thin (~ 0.006 mm) platinum overcoat. The NASA Nascoat 70 coating was applied by SD of a ductile low aluminum containing NiCrAlSi alloy followed by PC aluminization in which about one-half of the SD coating was converted to a nickel aluminide. The Airco Temescal ATD-1 coating was applied by PVD of a high aluminum and chromium containing NiCrAlY alloy. (See refs. 11, 13, 14, and 15 for more process details.) The thickness of these coatings were in the range of about 0.07 to 0.15 millimeter. Prior to burner rig testing, the specimens were degreased in acetone, rinsed in alcohol, dried, and weighed to 0.1 milligram.

The two high gas velocity burner rigs (Mach 1 and Mach 0.3) employed are shown in figures 2 and 3, respectively. In each rig, eight test specimens were placed in a holder which was rotated at 450 rpm directly in front of the exhaust nozzle. In the tests, the specimens were heated to a maximum surface temperature of 1100°C , held for 1 hour in the flame, and then subjected to a 3-minute air blast quench (Mach 1 blast in the Mach 1 tests and a Mach 0.7 blast in the Mach 0.3 tests). The specimens were tested up to 1250 cycles. Natural gas was used as the fuel in the Mach 1 tests while in the Mach 0.3 tests, Jet A-1 grade fuel was used. Both rigs simulated the oxidizing environments found in gas turbines. The rigs and their operations are described more fully in references 16 and 17. At least three times each week, the specimens were removed for weighing. The specimens were photographed at about 100-hour intervals and at the end of testing. In general, the specimens were tested until the coatings had visually failed. After test, the specimens were sectioned through the zone of maximum attack, metallographically prepared, and examined.

RESULTS AND DISCUSSION

Macroscopic Analysis

The macroscopic appearance of several coated ODS NiCrAl specimens is shown in figures 4 and 5 after various Mach 1 test times at 1100°C . Figure 4 presents post-test photographs showing Mach 1 TD-NiCrAl specimens coated with three overlay coatings. Two of four specimens coated with PWA 267 experienced some flaking and blistering (fig. 4(a)) in 500-test hours or less probably because of poor coating adherence. (The PWA 267 was deposited as it was on conventional superalloys.) On

the remaining two specimens, thermal fatigue cracks were first observed after about 600 hours of testing and oxidation attack of the substrate started after about 700 hours. After 790 test hours, however, serious leading edge (see fig. 1) attack and cracking was observed (fig. 4(b)). It was reported (refs. 13 and 14) that platinum additions to NiCrAl overlays have improved oxidation resistance. These platinum modified coatings on a nickel-base directionally solidified eutectic alloy ($\gamma/\gamma' - \delta$) have shown no failures in excess of 1000 hours in 1100⁰ C burner rig tests. Figure 4(c), however, shows that the PWA 267 + Pt coating experienced serious degradation at the leading and trailing edges in less than 600 hours. (Thermal fatigue cracking and leading edge coating failure were first observed after about 350 and 380 hours, respectively.) It is generally believed that life of overlay coatings increases with coating thickness. Thus, it is likely that premature failure of the PWA 267 + Pt coating on TD-NiCrAl can be partly due to its reduced thickness as compared to that of the unmodified overlay (0.069 mm compared to 0.097 mm). While the unmodified coating was the significantly better of the two PWA 267 coatings on TD-NiCrAl, it was not as good as Nascoat 70 which fully protected TD-NiCrAl from oxidation attack for more than 800 hours (fig. 4(d)). Only after about 850 hours at 1100⁰ C did Nascoat 70 show failure at the trailing edge of the specimen. (The maximum temperature at the trailing edge has been reported (ref. 18) to be higher than that at the leading edge.) This failure was severe and extensive after 1000 hours (fig. 4(e)). Thermal fatigue cracking of Nascoat 70 specimens, however, was first observed at about the same time as that for the PWA 267 coated specimens, i. e., 600 hours. All the specimens tested in Mach 1 rig experienced bowing because of poor creep strength. The optimum texture for ODS alloys was not obtained during extrusion of the TD-NiCrAl alloy. However, the alloy was considered useful for evaluating coatings.

Figure 5 shows similar photographs of coated YD-NiCrAl specimens after tests in a Mach 0.3 burner rig. Six of the eight specimens coated with the PWA 267 overlay experienced bulging and/or wrinkling followed soon thereafter by cracking of the coating. Here these premature failures (one of which is illustrated in fig. 5(a) taken after 140 hr) generally occurred in less than 250 test hours. Again these premature failures can probably be attributed to poor adherence of the PWA 267 coating. The remaining two PWA 267 coated specimens and all eight specimens with the ATD-1 coating experienced the onset of coating failure after about 1000 hours of testing. As long as a good adherent coating had previously been applied, no discernible difference could be assessed regarding coating failure time for the two overlay coatings.

Gravimetric Analysis

In general, these macroscopic observations are reinforced by the specific weight change (ΔW) data given in figures 6 and 7. Included here are comparative data for the two ODS alloys similarly tested, but in the uncoated, bare condition. General comparison of these data suggests that the Mach 1 tests were slightly more severe than the Mach 0.3 tests because of the higher weight losses in the former tests. This observation is similar to that reported in reference 2 and is probably related to the difference in cooling rates and to the difference in specimen geometries. In figure 6, the ΔW data for the PWA 267 coating represents the data obtained for one specimen which unfortunately was lost during an overtemperature excursion of the burner rig after 800 cycles. Although these data suggest that the PWA 267 coating protected TD-NiCrAl for 800 hours, the above macroscopic observations indicate that the coating began to fail after about 700 hours. Its rate of degradation (weight loss per cycle), however, was slower by comparison than that of Nascoat 70 or PWA 267 + Pt.

The inherent good oxidation resistance of these coatings and the ODS alloy is attributed to the formation of a dense, stable, nonvolatile oxide, Al_2O_3 (refs. 2, 8, 10, 11, 13, and 14). Data in figure 6 show that all the coated specimens experienced weight gains initially which coincided with the development of a protective Al_2O_3 scale. This was confirmed by X-ray diffraction. With increasing time, however, the specimens exhibited weight decreases as a consequence of gradual depletion of aluminum in the surface layer because of repeated spalling and formation of Al_2O_3 in addition to coating-substrate interdiffusion (ref. 19). Limited microprobe analyses of PWA 267 coated specimens before and after 500 hours of testing showed significant diffusion of aluminum into the substrates. After a sufficiently long time (in excess of 500 hr), the aluminum activity in the surface layer had decreased to less than that required for the formation of a Al_2O_3 scale. With increasing time, this resulted in large, rapid weight losses due to spalling of less protective oxides (NiAl_2O_4 , NiCr_2O_4 , and/or Cr_2O_3). Limited X-ray diffraction results showed the presence of a spinel (probably NiAl_2O_4) on the specimens after 500 test hours. These results and propositions are in general agreement with those reported in references 2, 8, 10, 11, 13 and 14. The data presented in figure 6 also confirm that Nascoat 70 had a higher aluminum containing surface layer and a larger aluminum reservoir. The basis for this is that Nascoat 70 coated specimens generally showed higher positive ΔW 's and longer times before experiencing negative ΔW 's compared to the other specimens in the Mach 1 tests. Also, the X-ray diffraction results appeared to support these assumptions; relative pattern intensities for β NiAl and Ni solid solutions were moderate and very strong, respectively, on the PWA 267 specimens, and very strong and nonexistent on the Nascoat 70 specimens.

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Figure 7 shows ΔW data for the PWA 267 and ATD-1 overlay coatings on a YD-NiCrAl alloy obtained in the Mach 0.3 tests. Similar data for uncoated YD-NiCrAl (from ref. 20) are included for comparison. These data show that for times in excess of 600 hours, both coatings were about equally protective on YD-NiCrAl. The slightly lower weight losses and rate of coating degradation of the PWA 267 coated specimens are believed to be partly due to these specimens having much larger radii at the edges and corners than those of the ATD-1 coated specimens. Comparison of the former specimens before and after testing indicated that the coating vendor had generously rounded the edges and corners of the specimens before coating. During burner rig testing, there would be a much lesser tendency for cracking of the coating with attendant weight losses at well rounded edges and corners. The ATD-1 coated specimens did indeed show cracks at the sharp corners during testing while the PWA 267 coated specimens did not. Thus, up through 600 hours, the performance of the PWA 267 coating on rounded cornered specimens was significantly better than the ATD-1's performance; the ATD-1 coating exhibited weight losses sooner and more rapidly than the uncoated ODS alloy. The PWA 267 coated specimens showed small weight gains initially whereas the uncoated and the ATD-1 coated specimens experienced only weight losses from start until a protective oxide was formed. The initial weight gains of the PWA 267 coated specimens are believed to be due to the formation of the protective Al_2O_3 oxide followed by weight losses attributed to spalling of Al_2O_3 and the less protective oxides as discussed previously. For the uncoated YD-NiCrAl specimens, it is felt that in the interval between 200 and about 1200 hours (see fig. 7) an Al_2O_3 scale had formed since the specimens exhibited a negligible weight change in this time interval. Thereafter, the uncoated specimens probably lost weight in the same manner as that proposed above. In the case of the ATD-1 coated specimens, the weight losses between 200 and 1200 hours may be due to some spalling of Al_2O_3 and/or Cr_2O_3 vaporization. Since the ATD-1 coating has a relatively high chromium content (i. e., 35 w/o), some Cr_2O_3 may have formed which readily vaporized in the high velocity oxidizing environment (ref. 21). The data of figure 7 also shows that the uncoated YD-NiCrAl alloy has sufficient inherent oxidation resistance for at least 1600 hours under the less severe Mach 0.3 test conditions (lower velocity, generous leading edge radius). However, these data and the macroscopic observations reported previously suggest that if coating and substrate lives are cumulative the life of YD-NiCrAl under these conditions could be extended an additional 1000 hours by using either a PWA 267 or an ATD-1 coating.

Metallographic Analysis

The metallographic results of coated ODS alloys before and after Mach 1 tests at 1100°C are presented in figure 8. The photographs on the left of the figure show the

specimens in the as-coated conditions. Those on the right show the cross-sectional metallography of the maximum attack zone at the leading edges (see fig. 1) of the coated specimens after tests for the times indicated. All coatings on the ODS alloy had undergone minimal (sides) to very extensive degradation (leading and/or trailing edges) during the cyclic burner rig tests depending on location. Since the PWA 267 coating on TD-NiCrAl in figure 8(b) shows almost complete oxide penetration in 500 hours in the Mach 1 tests, the coating would not be expected to offer substantially more hours of additional protection. As is clearly evident in figure 8(d), the platinum modified PWA 267 coating on the same ODS alloy was totally degraded in similar tests in less than 930 hours. In contrast, the Nascoat 70 coating on TD-NiCrAl (fig. 8(e)) appeared almost fully intact after 1000 hours of 1100^o C cyclic-oxidation testing in the sonic velocity, Mach 1 burner even though, as previously mentioned, a trailing edge failure resulted in a more rapid weight loss than that for the PWA 267 coating. Figure 8(f) shows some oxide penetration into the outer edge of the coating, but the coating is still protecting the substrate at the leading edge of the specimen. At this time, however, the coating at the trailing edge (not shown in fig. 8) was not protective as previously discussed (see Macroscopic Analysis section and fig. 4(e)).

Figure 9 shows a similar set of photomicrographs of PWA 267 and ATD-1 coatings on a YD-NiCrAl alloy substrate before and after cyclic tests in the Mach 0.3 burner rig. Nascoat 70 was not evaluated in the Mach 0.3 rig tests. While both coatings are thinner after more than 1200 hours of testing than in the as-coated conditions, the leading edge of the tested PWA 267 coated specimen (fig. 9(b)) surprisingly shows very little, if any, oxidation attack of the ODS alloy. This may be due to the coating separation observed which occurred without coating cracking. Also along the sides and trailing edge of this specimen, the coating-substrate interface contains pores which are almost interconnected throughout. On one side near the trailing edge of the specimen, however, the coating had failed (see fig. 5(a)). In contrast, the tested ATD-1 coated specimen presented in figure 9(d) shows oxide penetration throughout the coating and extensive oxidation attack of the ODS substrate at the specimen's leading edge. This specimen also showed extensive porosity along the sides and trailing edge in the coating-substrate interface.

There is some internal substrate porosity evident in the photos of the tested specimens presented in figures 8 and 9. Figures 8(b) and (f) also show significant porosity at the coating-substrate interfaces. Microprobe analysis on the PWA 267 coated TD-NiCrAl specimen after test, figure 8(b), showed a higher aluminum content in the coating and decreasing aluminum content through the coating-substrate interface and well into the substrate. (Microprobe analyses were not conducted on

the other specimens.) This would suggest that the porosity formed before coating failure is not due to the Kirkendall effect of aluminum diffusion from the substrate into the coating. Such an effect would have prevailed if the aluminum content of the coating was lower than that of the substrate. Such an aluminum loss could occur by the forming and then spalling of the Al_2O_3 scale in the burner tests. It is proposed that perhaps the early void formation is due to the coating-substrate interface serving as a sink for diffusion and annihilation of the dislocations formed during the thermo-mechanical processing of the ODS alloys. Eventually, aluminum loss would be sufficient to cause coating failure. At that time the porosity would probably be due to the Kirkendall effect (ref. 2). This porosity would certainly have a detrimental effect on the mechanical properties of the ODS alloys. The formation of serious porosity within the substrates might be extended to longer times if suitable barriers to aluminum diffusion could be developed for the coated ODS alloy systems.

CONCLUDING REMARKS

Although the overlay coatings on TD-NiCrAl and YD-NiCrAl alloys were burner rig tested for up to 1250 hours rather than to the desired 3000 hours, the results indicate that Nascoat 70, PWA 267, and ATD-1 coatings are useful for prolonging the onset of substrate attack to at least 700 hours and perhaps up to about 1000 hours before serious substrate attack occurs. The ODS alloys used in this study were nonoptimized (refs. 1 and 12).

In a recently completed study (ref. 20), however, Lowell and Deadmore concluded that the latest optimized YD-NiCrAl alloy has sufficient oxidation resistance for 3000-hour service at 1100°C without the need of a coating. The basis for this conclusion was that the optimized, uncoated alloy showed very little weight loss and microstructural attack after 3000 hours of testing at 1100°C in the Mach 0.3 burner rig. Thus, if all thermo-mechanical property goals are achieved, it would appear that completely optimized ODS alloys might be used in vane applications uncoated.

SUMMARY OF RESULTS

The purpose of this exploratory study was to examine the cyclic oxidation performance of several Ni-base overlay coatings on two ODS NiCrAl vane alloys at 1100°C in high velocity gas streams. The following five coating-ODS alloy combinations were examined:

Coatings on TD-NiCrAl ODS alloys (Ni-16Cr-4.6Al-2.07ThO₂)

<u>Designation</u>	<u>Type^(a)</u>	<u>Nominal composition</u>
PWA 267	PVD NiCrAlY	Ni-18Cr-12Al-0.3Y
PWA 267 + Pt	PVD NiCrAlY + SD Pt	(Ni-18Cr-12Al-0.3Y) + Pt
Nascoat 70	SD NiCrAlSi + PC Al	(Ni-16Cr-6Al-1.0Si) + Al

Coatings on YD-NiCrAl ODS alloys (Ni-16Cr-4.6Al-1.9Y₂O₃)

<u>Designation</u>	<u>Type^(a)</u>	<u>Nominal composition</u>
PWA 267	PVD NiCrAlY	Ni-18Cr-12Al-0.3Y
ATD-1	PVD NiCrAlY	Ni-35Cr-11Al-0.5Y

^aPVD = Physical vapor deposited

SD = Sputter deposited

PC = Pack cementation

Performance testing of coated TD-NiCrAl alloys was done in a Mach 1 burner rig for times up through 1000 hours; coated YD-NiCrAl alloys were tested in a Mach 0.3 burner rig for up to 1250 hours. Each cycle consisted of a 1-hour exposure at 1100° C followed by a 3-minute air blast quench. Macroscopic, gravimetric, and metallographic analyses were used to judge the protective ability of the coatings. The following major results were obtained:

Mach 1 tests

1. Nascoat 70 coating on TD-NiCrAl generally exhibited the best performance. For example, the substrate did not exhibit oxidation attack for about 850 hours of testing. In comparison, PWA 267 was slightly less protective. However, although it experienced the onset of coating failure after 700 hours its inherent rate of degradation (weight loss per cycle) was slower. The thermal fatigue resistance of Nascoat 70 and PWA 267 coated specimens was apparently similar since the specimens first showed cracking at about the same time (600 hr).

2. The oxidation and thermal fatigue resistance of the PWA 267 + Pt coating was judged less promising on TD-NiCrAl. Serious cracking and coating degradation occurred in less than 600 hours.

Mach 0.3 tests

3. PWA 267 and ATD-1 coatings were about equally protective on YD-NiCrAl. These coatings generally failed after about 1000 hours of testing.

General Observations

4. After test, all coated specimens showed porosity in the ODS substrates.

5. Many of the PWA 267 coated specimens (not optimized for ODS alloy substrates) exhibited poor coating adherence and prematurely failed on these new alloys by flaking.

REFERENCES

1. Klarstrom, D. L. and Grierson, R.: Optimization of an Oxide Dispersion-Strengthened Ni-Cr-Al Alloy for Gas Turbine Engine Vanes. (Cabot Corp.; NASA Contract NAS3-17806.) NASA CR-134901, 1975.
2. Deadmore, Daniel L.; Lowell, Carl E.; and Santoro, Gilbert J.: High Gas Velocity Oxidation and Hot Corrosion Testing of Oxide Dispersion-Strengthened Nickel-Base Alloys. NASA TM X-71835, 1975.
3. Klechka, Ernest W.; and Grisaffe, Salvatore J.: Exploratory Studies on Modified Aluminide Coatings for Low Carbon and Stainless Steels. NASA TM X-2201, 1971.
4. Smialek, James L.: Exploratory Study of Oxidation-Resistant Aluminized Slurry Coatings for IN-100 and WI-52 Superalloys. NASA TN D-6329, 1971.
5. Johnston, James R.; and Young, Stanley G.: Oxidation and Thermal Fatigue of Coated and Uncoated NX-188 Nickel-Base Alloy in a High-Velocity Gas Stream. NASA TN D-6795, 1972.
6. Smialek, James L.: Fused Silicon-Rich Coatings for Superalloys. NASA TM X-3001, 1974.
7. Moore, V. S.; Brentnall, W. D.; and Stetson, A. R.: Evaluation of Coatings for Cobalt- and Nickel-Base Superalloys, Volume II. (RDR-1474-3, Solar; NASA Contract NAS3-9401.) NASA CR-72714, 1970.
8. Talboom, F. P.; Elam, R. C.; and Wilson, L. W.: Evaluation of Advanced Superalloy Protection Systems. (PWA-4055, Pratt and Whitney Aircraft, NASA Contract NAS3-12415.) NASA CR-72813, 1970.
9. Levinstein, M. A.; and Stanley, J. R.: Improved Aluminide Coatings for Nickel-Base Alloys. (General Electric Co.; NASA Contract NAS3-11160.) NASA CR-72863, 1971.
10. Deadmore, Daniel L.: Cyclic Oxidation of Cobalt-Chromium-Aluminum-Yttrium and Aluminide Coatings on IN-100 and VIA Alloys in High-Velocity Gases. NASA TN D-6842, 1972.
11. Gedwill, Michael A.; and Grisaffe, Salvatore, J.: Aluminized Alloy Boosts Turbine Blade Life. Metal Progress, vol. 106, no. 3, Aug. 1974, pp. 66-68.

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12. Klinger, L. J.; et al.: Development of Dispersion Strengthened Nickel-Chromium Alloy (Ni-Cr-ThO₂) Sheet for Space Shuttle Vehicles, Part 2. (Fansteel, Inc.; NASA Contract NAS3-13490.) NASA CR-121164, 1972.
13. Felten, E. J.; Strangman, T. E.; and Ulion, N. E.: Coatings for Directional Eutectics. (PWA-5091, Pratt and Whitney Aircraft; NASA Contract NAS3-16792.) NASA CR-134735, 1974.
14. Strangman, T. E.; Felten, E. J.; and Benden, R. S.: Refinement of Promising Coating Compositions for Directionally Cast Eutectics. (PWA-5441, Pratt and Whitney Aircraft, NASA Contract NAS3-18920.) NASA CR-135103, 1976.
15. Boone, D. H.: Overlay Coatings for Improved Oxidation/Corrosion Protection and Ductility for High Temperature Applications. Aircor Temescal, 2850 Seventh Street, Berkeley, CA, 94710, May 1977.
16. Johnston, James R.; and Ashbrook, Richard L.: Effect of Cyclic Conditions on the Dynamic Oxidation of Gas Turbine Superalloys. NASA TN D-7614, 1974.
17. Gray, Hugh R.; and Sanders, William A.: Effect of Thermal Cycling in a Mach 0.3 Burner Rig on Properties and Structure of Directionally Solidified $\gamma/\gamma' - \delta$ Eutectic. NASA TM X-3271, 1975.
18. Johnston, James R.; and Ashbrook, Richard L.: Oxidation and Thermal Fatigue Cracking of Nickel- and Cobalt-Base Alloys in a High Velocity Gas Stream. NASA TN D-5376, 1969.
19. Smialek, James L.; and Lowell, Carl E.: Effects of Diffusion on Aluminum Depletion and Degradation of NiAl Coatings. NASA TM X-68274, 1973.
20. Lowell, Carl E.; and Deadmore, Daniel L.: High Velocity Oxidation and Hot Corrosion Resistance of Some ODS Alloys. NASA TM X-73656, 1977.
21. Kohl, Fred J.; and Stearns, Carl A.: Vaporization of Chromium Oxides from the Surface of TD-NiCr under Oxidizing Conditions. NASA TM X-52879, 1970.

TABLE I. - ANALYSIS OF ODS ALLOYS (w/o)

Alloy	Constituent					
	Ni	Cr	Al	ThO ₂	Y ₂ O ₃	S
TD-NiCrAl (3933 alloy)	Bal.	16.22	4.63	2.03	---	0.001
YD-NiCrAl (MOD HA8077 alloy AT -264)	Bal.	15.65	4.61	----	1.93	<.002

TABLE II. - COATINGS CHARACTERIZATION

Coating	Process ^(a)		Nominal overall thickness		Nominal composition of precoat (w/o)				
	Precoat	Overcoat							
				mm	mils	Ni	Cr	Al	Y
PWA 267	PVD NiCrAlY	None	$\left\{ \begin{array}{l} 0.097^{(b)} \\ .124^{(c)} \\ .069 \end{array} \right.$	3.8	Bal.	18.3	12.1	0.25	---
PWA 267 + Pt	PVD NiCrAlY	SD Pt		4.9	Bal.	18.3	12.1	.25	---
Nascoat 70	SD NiCrAlSi	PC Al		2.7	Bal.	15.5	5.7	----	1.0
ATD-1	PVD NiCrAlY	None	.147 ^(d)	5.8	Bal.	35.0	11.0	.5	---
			.109	4.3	Bal.				

^aPVD, physical vapor deposition; SD, sputter deposition; and PC, pack cementation.

^bPWA 267 coating on TD-NiCrAl test bars.

^cPWA 267 coating on YD-NiCrAl test bars.

^dNascoat 70 precoat thickness, 0.124 mm (4.9 mils).

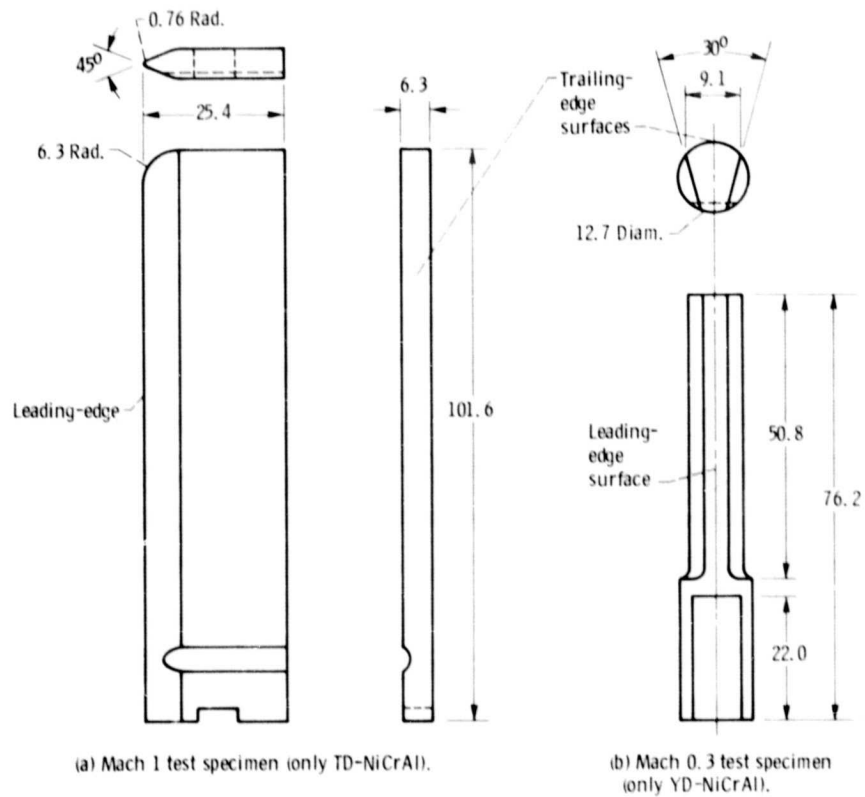
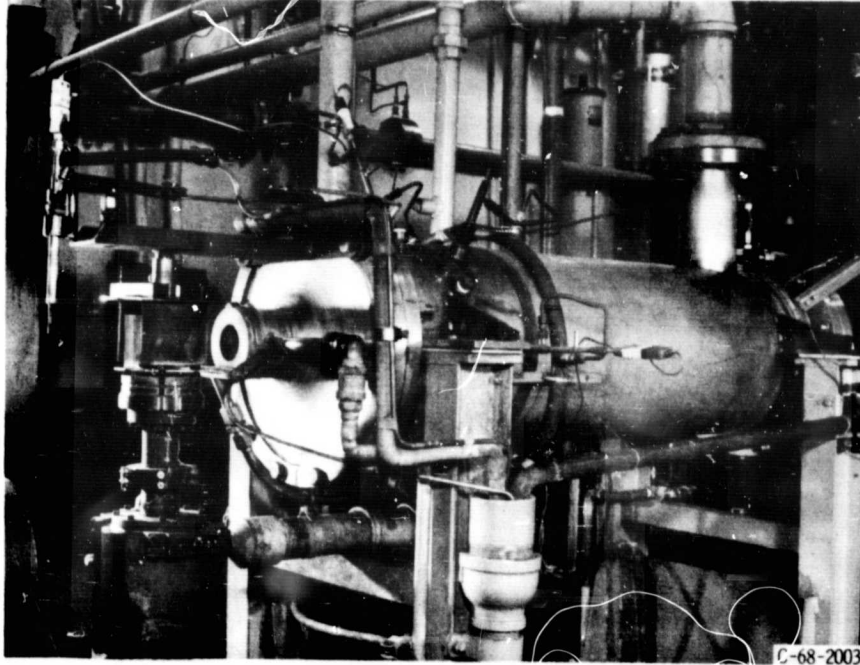
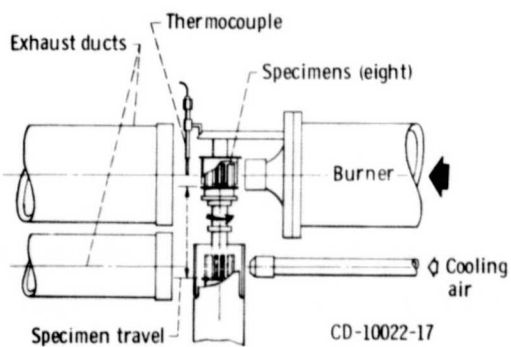


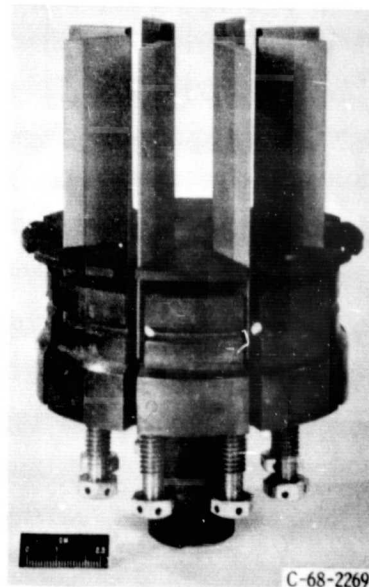
Figure 1. - High velocity burner rig test specimens. Dimensions in mm.



(a) Overall view.



(b) Schematic diagram.



(c) Specimen holder assembly.

Figure 2. - Mach 1 oxidation apparatus.

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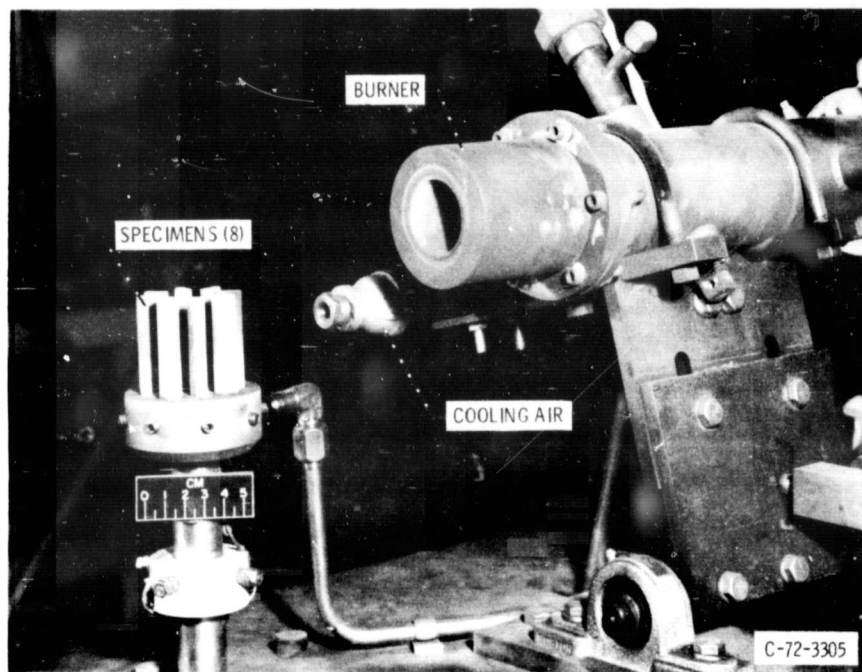


Figure 3. - Mach 0.3 oxidation apparatus.

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(a) PWA 267 COATED
TD-NiCrAl AFTER 500 HRS.

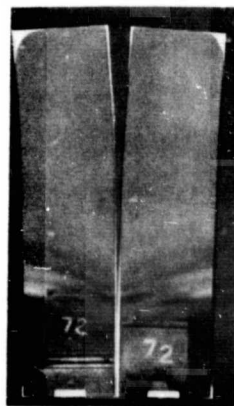


(b) PWA 267 COATED
TD-NiCrAl AFTER 790 HRS.

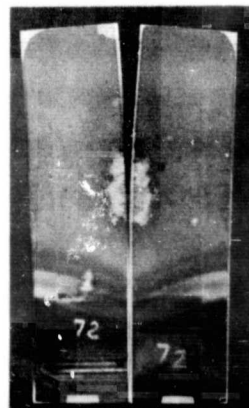


(c) PWA 267+Pt COATED TD-
NiCrAl AFTER 582 HRS.

Figure 4. - Photomicrographs showing surface appearance of coated TD-NiCrAl after cyclic oxidation at 1100°C in the Mach 1 burner rig. (One hour cycles).

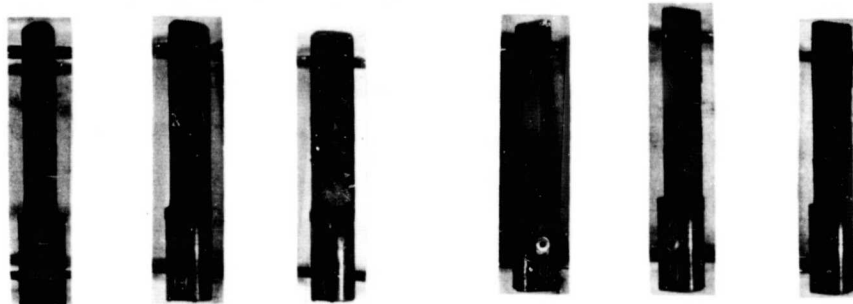


(d) NASCOAT 70 COATED
TD-NiCrAl AFTER 800 HRS.



(e) NASCOAT 70 COATED
TD-NiCrAl AFTER 1000 HRS.

Figure 4. - Concluded.



AFTER 140 HRS. AFTER 994 HRS. AFTER 1249 HRS.

(a) PWA 267 COATED YD-NiCrAl.

AFTER 731 HRS. AFTER 1097 HRS. AFTER 1245 HRS.

(b) ATD-1 COATED YD-NiCrAl.

Figure 5. - Photomicrographs showing surface appearance of coated YD-NiCrAl after cyclic oxidation at 1100°C in the mach 0.3 burner rig. (One hour cycles.)

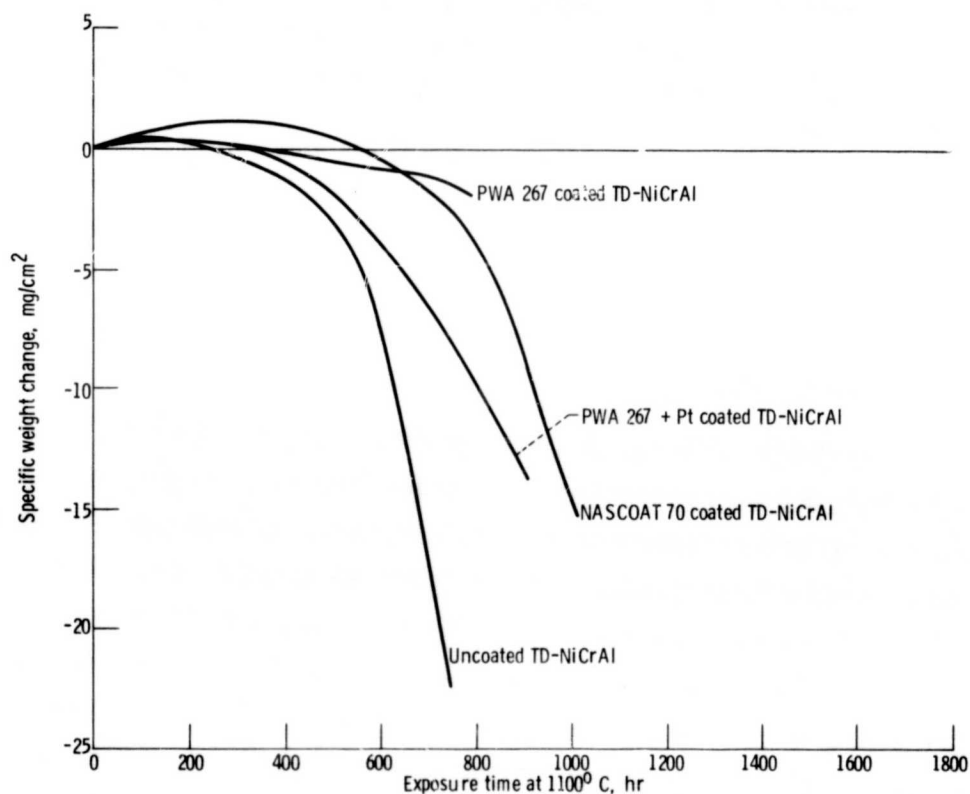


Figure 6. - Mach 1 burner rig oxidation of TD-NiCrAl at 1100°C. One hour cycles.

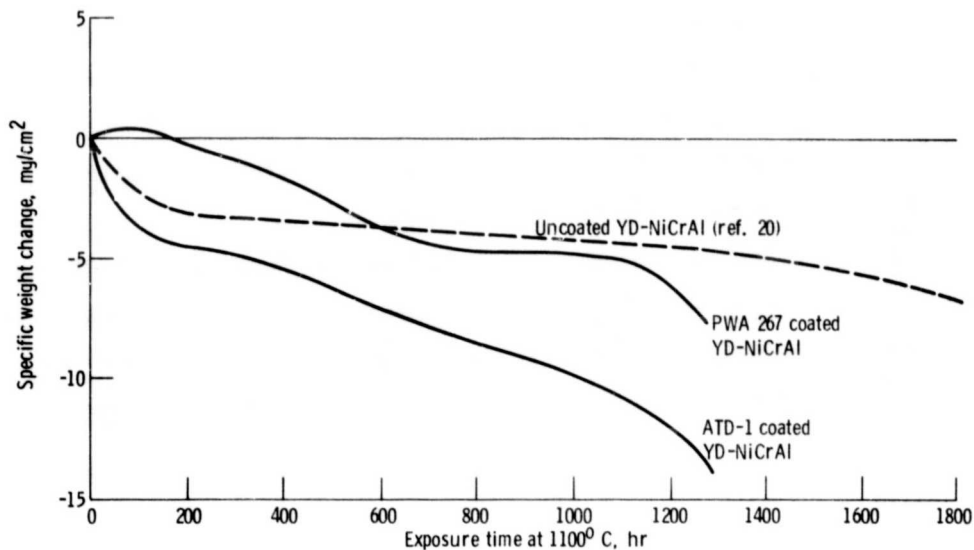
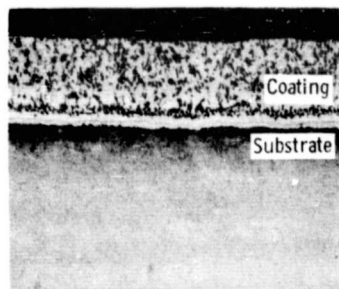
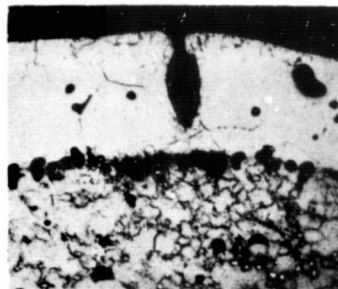


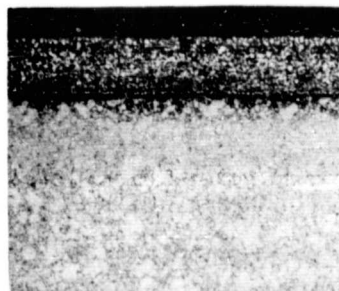
Figure 7. - Mach 0.3 burner rig oxidation of YD-NiCrAl alloys at 1100°C. One hour cycles.



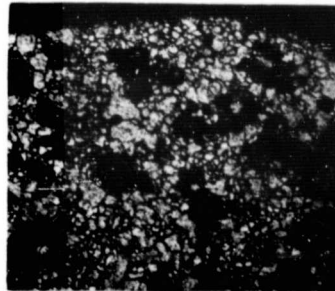
(a) PWA 267 coated TD-NiCrAl as coated. Coating thickness, ~0.097 mm (3.8 mils).



(b) PWA 267 coated TD-NiCrAl. Leading edge after 500 hours.

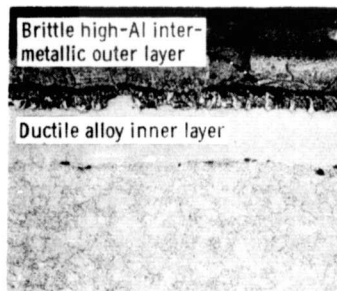


(c) PWA 267 + Pt coated TD-NiCrAl as coated. Coating thickness, ~0.069 mm (2.7 mils).

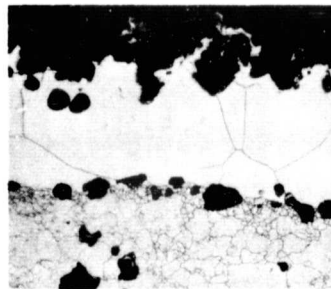


(d) PWA 267 + Pt coated TD-NiCrAl. Leading edge after 930 hours.

Figure 8. - Photomicrographs showing the effect of ultra high velocity, Mach 1 burner rig oxidation of coated TD-NiCrAl. One hour cycles at 1100°C. X250.

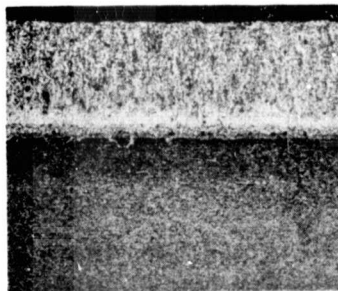


(e) Nascoat 70 coated TD-NiCrAl as coated. Coating thickness, ~ 0.147 mm (5.8 mils).

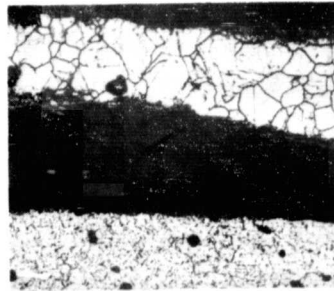


(f) Nascoat 70 coated TD-NiCrAl. Leading edge after 1000 hours.

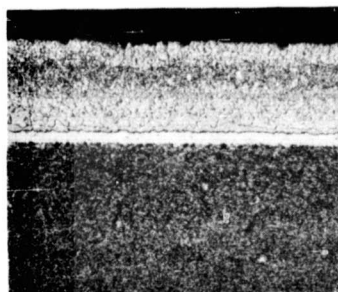
Figure 8. - Concluded.



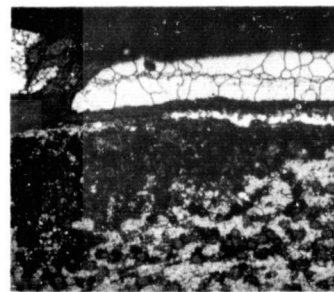
(a) PWA 267 Coated YD-NiCrAl as coated. Coating thickness, ~ 0.124 mm (4.9 mils).



(b) PWA 267 coated YD-NiCrAl. Leading edge after 1249 hours.



(c) ATD-1 coated YD-NiCrAl as coated. Coating thickness, ~ 0.109 mm (4.3 mils).



(d) ATD-1 coated YD-NiCrAl. Leading edge after 1245 hours.

Figure 9. - Photomicrographs showing the effect of high velocity, Mach 0.3 burner rig oxidation of coated YD-NiCrAl. One hour cycles at 1100° C. X250.

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